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Consideration of methods of orienting the human body under conditions of weightlessness in the absence of a support. Various techniques for making the body rotate by moving the arms and legs are described. It is shown that the most favorable methods of rotating the body are those initiated by movements of the legs. A rotation where the legs are spread apart in a scissors-like fashion in the front-to-back direction is singled out for particular attention and is recommended as the main method to be used in orienting the body about its longitudinal axis.

After A.A.Leonov stepped into space, the editorial board of the Journal "Aviatsiya i Kosmonavtika" received many letters in which the readers requested that we relate in greater detail the possibilities of a person moving in free space. This problem had already been explained to some extent in the speeches by P.I.Belyayev and A.A.Leonov and in the reports of newspaper correspondents.

The following article will familiarize the reader with the theoretical principles of biomechanics of human movement in free space.

A study of the qualitative and quantitative characteristics of various methods of man's movements in space has become an urgent problem. We want to examine one of the questions of this complex problem, namely, the methods of orientation of a human subject in a weightless state in the absence of a support.

* Numbers in the margin indicate pagination in the original foreign text.

The movements of a body, particularly the orientation in free space, have occupied the minds of scientists for a long time. Many experts in mechanics previously considered that a living creature cannot turn his body about some axis in an unsupported position. As their basic argument they cited the law of conservation of moment of momentum (law of areas). For example, the well-known French mathematician Delaunay in his book "Mechanics" (1862) wrote: "If we assume that some living creature is isolated in space and that no external force is applied to it, then not only will this living being be unable to displace its center of gravity, but furthermore it will prove impossible for it to impart rotation to its body about this point. Actually, no matter what muscles the human subject would flex, he will be able to generate only internal forces; the absence of external forces has the consequence that the sum of the described areas, projected onto an arbitrary plane passing through the center of gravity, will retain a constant value; thus, it must constantly remain equal to zero."

The erroneousness of such assertions was proved by Deprez. He took several photographs of a falling cat which, without particular difficulty, always turned feet downward. It seemed that this fact was inexplicable from the point of view of the fundamental law of mechanics, namely, the law of areas.

However, Prof.V.Kirpichev demonstrated that the turning of the cat was in full agreement with the law of areas. In his book "Discussions on Mechanics" (1907) he wrote: "... a man or an animal cannot impart to himself a rotation /49 which a spinning top or other completely fixed body produces. However, living creatures can produce diverse movements by their own individual limbs: The arm or leg can be turned relative to the rest of the torso, so that the creature can select those motions which compensate turning of the entire torso; that is, these additional movements of the arms and legs yield an area which is equal, but inverse in sign, to the area described by the remaining body rotating about some axis. Thus, the phenomenon of this rotation will not contradict the law of areas."

Consequently, according to Kirpichev's findings, a human subject, without interaction with extraneous bodies, can turn his trunk relative to some axis provided he turns some other part of the body in an opposite direction. This hypothesis is easily proved experimentally. For example, if a human subject stands erect on a horizontal platform, placed on a sphere which is able to rotate without drag, i.e., a Zhukovskiy bench (the force of friction can be disregarded in this case), and describes conical movements with his arm over his head relative to the longitudinal axis of his body, he will impart a rotation to his body in the opposite direction without the action of an extraneous force.

R.Pol' in his book "Introduction to Mechanics and Acoustics" (1930) demonstrated, on the same basis as Kirpichev, that man can turn his body by moving his arm in a different manner. The essence of this was that the subject first moves his arm to the limit in a horizontal plane in front of himself, which causes the remaining part of the body to turn in the opposite direction through a certain angle; he then returns the arm to the initial position but not along the original path since this would cancel the turn gained.

Can a person quickly turn his body by moving his arms? There are a number of hypotheses in the literature concerning this.

It is stated in textbooks on biomechanics that, under the effect of internal forces, a body can turn about a vertical axis (e.g., turning of the body to the left by swinging the arms left to right)at a negligible speed. It is obvious that Prof.M.Ivanitskiy (1948) wanted to emphasize the same, when he indicated that for turning the body (somersault) without a starting rotational momentum it is necessary that its period of free flight be as long as possible.

Thus, the essence of all these hypotheses reduces to the fact that it is impossible to turn the body rapidly around a free axis by various movements of the arms. However, man can use the movement of not only his arms but also of his legs.

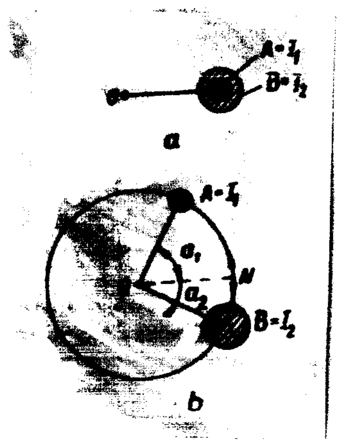

Fig.1 Diagram of the Interaction of Two Parts of the Body in an Unsupported Position during Muscle Contraction:
a - Position of body parts before interaction;
b - Position of body parts some time after the start of interaction.

In this article, we will attempt to describe the most common principles of motion of individual parts of the human body for its orientation in free space.

In order to define what type of movement of individual body parts is most advantageous for a rapid turning of the entire body, we must first examine the quantitative aspect of the process of their interaction. We will analyze this by means of a special diagram (Fig.1).

Let us assume that two parts of the human body interact relative to the axis OO (in our example, directed perpendicular to the plane of the paper): A and B which, before the start of the interaction, occupy the position as shown in the diagram (Fig.1,a). We will stipulate that the moment of inertia of the body A relative to the axis OO is equal to I_1 and that the moment of inertia of the body B is I_2.

If the subject exerts muscular force and turns the body part A through an angle a_1 in unit time, then the other part of the body, according to the Third Law of Mechanics, turns in the opposite direction through an angle a_2 so that the entire body will occupy the position shown in Fig.1,b. During the interaction, both parts of the body are given the same angular momentum: A will receive $K_1 = I_1 a_1$; B will receive $K_2 = I_2 a_2$. From the equality of the angular momentum, it follows that $I_1 a_1 = I_2 a_2$. If we develop the equality into a proportion, we obtain:

$$\frac{a_1}{a_2} = \frac{I_2}{I_1}.$$

Thus, the angular velocities (or the angles of rotation from the starting position) imparted to the interacting parts of the body are inversely proportional to their moments of inertia, i.e., the angle of rotation of the body part A, during a certain time interval, is as many times greater (less) than the angle of rotation of the body part B as its moment of inertia is less (greater) than the moment of inertia of B. /50

In Fig.1 it is assumed for convenience that the moment of inertia of the body B is twice that of the body A, so that $\angle a_2 = 30^\circ$ and $\angle a_1 = 60^\circ$.

If a person turns his body by arm movements, it is most preferable to hold the arm straight and move it in a plane perpendicular to the axis OO, keeping the body in an "attention" pose. With this method of interaction of the two body parts, rotation of the arm through a certain number of degrees will cause a maximal turn of the body in the opposite direction.

In order to say specifically through what angle the arm must be turned with this method, so as to turn the body in the opposite direction by a certain number of degrees, we must know the magnitude of the moments of inertia of the interacting parts of the body, relative to the axis OO.

We will find the moment of inertia of the arm and the remaining part of the body relative to the axis OO of the shoulder joint, directed parallel to the long axis of the body, for a man 170 cm tall and weighing 70 kg (mass of 70 kg), by using the data of biomechanics on the relative weights and sizes (proportions) of individual parts of the human body. According to the data cited in the textbook on biomechanics (Ye.Kotikova et al., 1939), at this height the distance from the long axis of the body passing through the common center of gravity to the axis OO is equal to 20 cm and from the center of gravity of the arm (elbow), 30 cm; the mass of the arm for the above weight is 4.5 kg and the mass of the remaining part of the body, 65.5 kg.

Now, to calculate the moments of inertia of the interacting body parts relative to the axis OO, it is only necessary to determine the moments of inertia of each part relative to its own center of gravity. For the human body, this value has been established only experimentally. According to the data by R.Pol', the moment of inertia of the human body relative to the long axis in a drill stance ("attention" posture) is 1.2 kg-m^2. This value, without major error, can be used for the human body without the mass of one arm. Thus, the moment of inertia of the body relative to the axis OO will be I_0 = 1.2 kg-m^2 + + 65.5 kg (0.2 m)^2 = 3.82 kg-m^2 (the moment of inertia of the body was determined by the formula

$$I_0 = I_c + ma^2,$$

where

I_c = moment of inertia relative to the axis passing through the center of gravity;

m = mass of the body;

a = distance from the center of gravity to the axis).

The moment of inertia of the arm relative to the transverse axis passing through its center of gravity is approximately equal to $I_e = m \cdot 0.09l^2$, where l is the length of the arm.

Fig.2 Motion Pictures of Turns by Moving both Arms
a - On a Zhukovskiy bench; b - In unsupported position

The arm length of a man 170 cm tall is 70 cm. Therefore, $I_0 = 4.5 \text{ kg} \cdot 0.09 (0.7 \text{ m})^2 \approx 0.2 \text{ kg-m}^2$, so that the moment of inertia of the arm relative to the axis OO will be /51

$$I_0 = 0.2 \text{ kg-m}^2 + 4.5 \text{ kg } (0.3 \text{ m})^2 \approx 0.6 \text{ kg-m}^2.$$

Thus, the ratio of the moments of inertia of the arm and the remaining part of the body of $\frac{0.6}{3.8}$ or about $\frac{1}{6}$ shows that, to turn through n°, it is necessary to rotate the arm in the opposite direction through an angle of $6n^\circ$. This means that to turn the body 180° it is necessary to rotate the arm in a plane perpendicular to the axis of rotation through an angle of $180^{\circ} \times 6$, i.e., the indicated movement must be repeated six times.

Fig.3 Motion Pictures of Turns by Leg Movements
a - On a "Zhukovskiy bench"; b - In an unsupported position

Our investigations on a "Zhukovskiy bench" and in an unsupported postiion (exercises on a trampoline) confirmed the correctness of the calculations. Thus, to turn the body 180° about the long axis by conical movements of one arm over the head, a total of 5 - 6 such movements must be made on the "Zhukovskiy bench". The same number of movements with one arm is needed in the mode of turning described by R.Pol'.

In our opinion, for a more rapid turn about the long axis it is better to use the movements of both arms in the opposite direction, in a plane perpendicular to the axis of rotation. To turn, for example, to the left one should assume an initial position in which the right arm is extended forward and the left as far back as possible (Fig.2, frame 1). One cycle of this method of turning consists of two phases of arm movements. In the first phase, the main one, the arms are moved fully to the right in a plane perpendicular to the axis of rotation, i.e., past the sides, so that at the end of the phase the right arm occupies the posterior position and the left, the anterior (frames 2 - 3).

In the second phase, the preparatory phase, the arms are moved in a sagittal plane, i.e., downward, to the starting position (frame 4).

To turn through 180° on a "Zhukovskiy bench" by this method it is necessary to make only about three cycles of arms movements.

In exercises on a trampoline, one must perform two cycles of arm movements and turn through 120 - 130° when in an unsupported position (1 - 1.5 sec) (Fig.2,b). In using this method of turning by conical movements of one arm, one can at best turn 70° in the same time.

The investigations also showed that it is best to use leg movements to turn. Thus, movement of the leg forward, to the side, and backward (half-circle) causes a 90° turn of the body (Fig.3,a), i.e., the moment of inertia of the leg in this case is only half that of the remaining part of the body. Furthermore, return of the leg by moving it forward to the starting position (like taking a step) scarcely causes a reciprocal movement of the body.

Even more effective and simple with respect to coordination is a turn /52
with spreading of the legs in an anteroposterior direction in a sort of "split" (Fig.3,b). To make a turn by this method, one must part the legs as if taking a wide step; turn around, rotating the legs toward the turn at the hip joints about their longitudinal axes; by a counter movement, return the legs to the starting position to repeat the cycle. One cycle of movements permits turning through 140 - 160°. Because of the simplicity of execution and the effectiveness of turning by making a "split", this can be recommended as the basic method in orientation around the long axis of the body.

A suitable ratio of moments of inertia of the interacting parts can be obtained by executing the turn from a bent or arched position of the body, i.e., by not keeping the long axes of the torso and legs on the same straight line but letting them intersect at some angle (Fig.4).

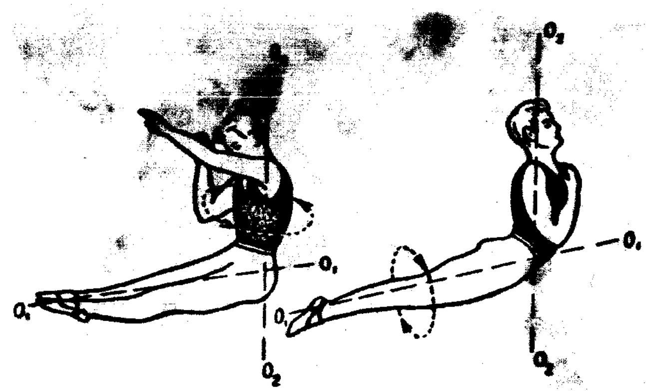

Fig.4 Spiral Turn from a Bent to an Arched Position

Calculations show that, at an angle of body flexion of 90 - 100°, the moment of inertia relative to the long axis of the torso O_2O_2 is about 7 - 8 times greater than the moment of inertia of the torso relative to this axis, and the moment of inertia of the torso relative to the longitudinal axis O_1O_1 is approximately as many times greater than that of the legs relative to their own longitudinal axis. Therefore, when turning the torso to the maximum possible angle, the legs move in the opposite direction about O_2O_2 through an angle 7 - 8 times smaller than the angle of rotation of the trunk. The same pattern will occur when turning the legs to the required side; in this case, at a maximal turn of the legs the trunk is only negligibly displaced about the axis O_1O_1 in the opposite direction. Thus, by successively turning first the trunk and then the legs at a suitable ratio of moments of inertia it is possible to turn in a spiral motion about the longitudinal axis at a high rate, up to 800 - 900° per second.

This method is rather complex with respect to coordination and requires great freedom of motion. Therefore, it can be performed only in a light gym suit. However, the rapidity of turning and the unique "naturalness" of the movements (endeavor to turn the trunk, head, and arms in the wanted direction) make the method quite desirable. Presumably, it will be convenient in use for orientation inside orbital space stations where the crew will work without space suits. Performing this turn involves conical movements of the legs and torso and thus also of the head. This latter is frequently the cause of considerable stimulation of the vestibular apparatus, due to the cumulative effect of Coriolis acceleration. However, since the average human being rarely has occasion to turn more than 180°, the danger of vestibulo-autonomic reactions in this case is no more than in any other method of turning.

To rotate the body about its transverse axis, i.e., in tangential orientation - as calculations have shown - the inertia ratios of the interacting body parts are most favorable when turning with the arms straight in an anteroposterior (sagittal) plane in a grouped body position. This method is simple with respect to coordination and does not require appreciable muscular exertion. To turn through 180°, about 6 - 7 circular motions of the arms to the opposite side are required since the moment of inertia of the arms relative to the axis of the shoulder joints is 12 - 14 times less than that of the remaining part of the body in a grouped position. When turning with the body straight, the number of rotational movements of the arms will be double, i.e., 12 - 14. However, this number can be reduced markedly if some object (for example, a tool) is held in the hands, thus increasing the moment of inertia of the arms. In particular, holding a hammer weighing 0.7 kg in each hand, it suffices to make only one circular movement of the arms in a sagittal plane instead of 3 - 4, in order to turn $45 - 50^{\circ}$ (Fig.5,a).

When moving about the anteroposterior axis, i.e., executing a rolling motion, the body should be oriented by circular movements of the arm in a frontal plane, to the side opposite of the turn of the whole body. Our calculations /53 showed that, for orientation in a $35 - 40^{\circ}$ roll, it is necessary to make 4 - 5 circular movements of one arm. If the moment of inertia of the arm is increased (by a hammer weighing 0.7 kg), only one and one-half circular movements of the arm need be made to turn the body the same number of degrees (Fig.5,b).

Fig.5 Motion Pictures of Body Orientation
a - Pitching; b - Rolling

The results of the investigations permit the assertion that, after some training, a person will be able, even when "floating" unsupported in a weightless state, to quickly and accurately orientate himself in any direction exclusively by muscular efforts, without resorting to technical aids. This capacity, in our opinion, must be taken into account when designing individual pack equipment for forward motion in cosmic space.

Apparently, a main booster rocket, with the jet issuing from the side of the back at the point of projection of the common center of gravity of the body and another (compensating) nozzle at the level of the shoulder line will be sufficient. The direction of flight of the astronaut can be changed by proper orientation of the body, using the described methods. It is believed that this principle will help to simplify and facilitate the design of the booster and make it more economical; no doubt, it will also become more convenient to operate.

Special ground training is necessary for reliably controlling the body when freely "swimming" in the weightlessness of space. The astronaut's movements must become automatic such as those of gymnasts, acrobats, divers, and other athletes who also must perform complex turns in the suspended phase.

The mastering of various methods of turning in free space is best begun with the performance of individual elements on a "Zhukovskiy bench". It is possible to reinforce the new motor stereotype, while gradually complicating the movements by exercises on trampolines, bars, or special stands. Acrobatics, and especially high diving, are beneficial for perfecting control of the body in free flight. Finally, a mandatory phase of training must comprise parabolic aircraft flights, during whose weightless period various movements, using prescribed implements and equipment, will be standardized. Furthermore, in such flights various manipulations should be performed, while using the required tools.

Cosmonaut A.Leonov opened the door into space and crossed the threshold. Others will follow him; they will build orbital stations, work in them, mastering and living in near-earth space. Next will be Moon, Mars, Venus... . However, this is a separate, no less complex and possibly more complex, problem.